Spatially separated excitons in 2D and 1D

David Abergel

March 10th, 2015

NORDITA

European Research Council
Established by the European Commission

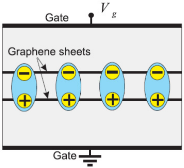
Outline

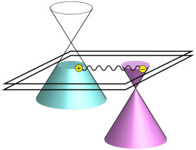
Introduction

NORDITA The fundamental idea

Key ingredients:

- Independent contacts to each layer
- High degree of nesting of Fermi surfaces
- Low SP tunneling rate between layers

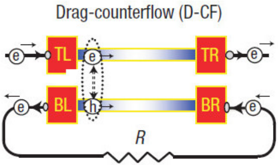




Picture credit: Kharitonov *et al.*, Phys. Rev. B **78**

Phase coherence between the two layers

Transport of excitons can be measured:



IEEE ELECTRON DEVICE LETTERS, VOL. 30, NO. 2, FEBRUARY 2009

Bilayer PseudoSpin Field-Effect Transistor (BiSFET): A Proposed New Logic Device

Sanjay K. Banerjee, *Fellow, IEEE*, Leonard F. Register, *Senior Member, IEEE*, Emanuel Tutuc, *Member, IEEE*, Dharmendar Reddy, and Allan H. MacDonald

Picture credit: Su *et al.*, Nat. Phys. **4**.

Apply current in lower layer, measure voltage drop in upper layer (drag measurement).

A new mechanism for superconductivity: pairing between spatially separated electrons and holes

Yu. E. Lozovik and V. I. Yudson

Spectroscopy Institute, USSR Academy of Sciences
(Submitted March 2, 1976)
Zh. Eksp. Teor. Fiz. **71**, 738–753 (August 1976)

A new mechanism for superconductivity, based on the pairing of spatially separated electrons and holes that arises from their Coulomb attraction, is proposed. A gap in the single-particle excitation spectrum is found. The roles of interband transitions, the electron-phonon interaction, scattering by impurities, spin-orbit interaction, etc. are analyzed. The critical current is calculated. Possible experiments are discussed.

PACS numbers: 74.30.—e

The maximum value of the gap Δ, equal in order of magnitude to the binding energy $E_0=m^*e^4/\varepsilon^2$ of an isolated pair, is attained when $m_e\sim m_h\sim m^*$ and $D\lesssim a^*\sim l$ (the strong-interaction regime, in which (8) has only the character of an estimate; $a^*=\varepsilon/m^*e^2$). If, e.g., $m^*=0.03m_0$ (m_0 is the electron mass) and $\varepsilon=3$, then $a^*\approx 50$ Å and for $D\sim l\sim 50$ Å we have $\Delta\sim 300$ K.

Prediction was formation of 'superconductivity' with gap of the order of room temperature.

The impact of disorder in 2D

with Enrico Rossi, Rajdeep Sensarma, and Martin Rodriguez-Vega, and Sankar Das Sarma.

- The condensate has yet to be observed despite several experimental attempts.
- Question is: Why?

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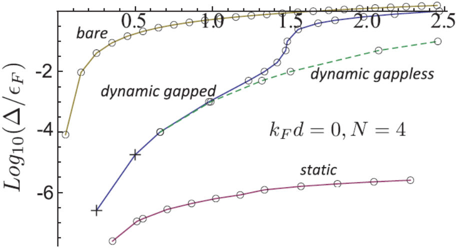
Possibility 1: Excitonic gap is too small.

The form of the inter-layer screening used in the calculation of the gap is crucial:



Sodemann *et al.*, Phys. Rev. B **85**, 195136 (2012).

For SiO_2 or BN substrates, $\alpha = \frac{e^2}{\kappa \hbar v_F} \approx 0.5$.
For vacuum (suspended graphene), $\alpha = 2.2$.

- Unscreened interaction $\Rightarrow$ room temperature condensate!!!
- Static screening $\Rightarrow$ vanishing gap.
- Dynamic screening $\Rightarrow$???

Double layer graphene – Excitonic superfluidity

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- Question is: Why?

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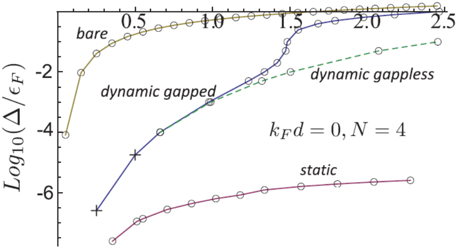

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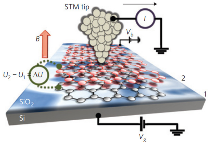
Possibility 2: Disorder

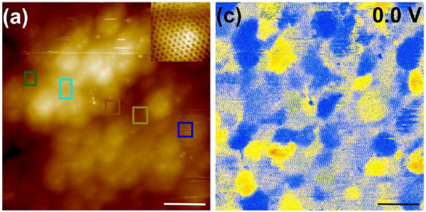
Disorder in graphene systems

- STM can reveal atomic-scale structure of crystal.
- Also resolve the Dirac point,
- Which can be used to extract the local charge density.



Rutter *et al.*, Nat. Phys. **7**, 649 (2009).

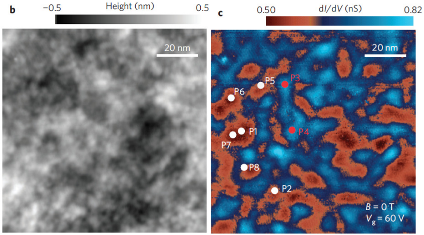
Monolayer:



Deshpande *et al.*, Phys. Rev. B **79**, 205411 (2009).

Scale bar is 8nm.

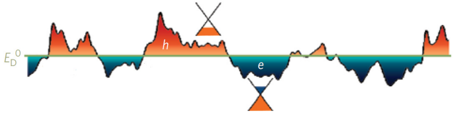
Bilayer:



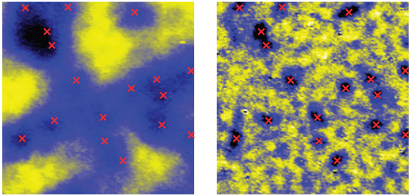
Rutter *et al.*, Nat. Phys. **7**, 649 (2011).

Scale bar is 20nm.

Scalar potential acts as a local shift in the chemical potential:

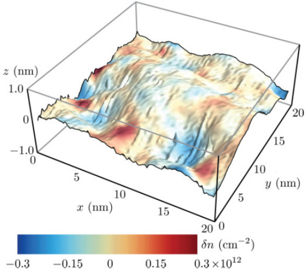


Charged impurities:



Zhang *et al.*, Nat. Phys. **5**, 722 (2009).

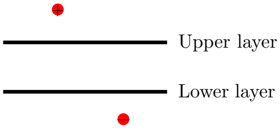
Ripples, corrugations, and strain:



Gibertini *et al.* Phys. Rev. B **85**, 201405(R) (2012).

Possibility 2 – Disorder

- Main question: Does charge inhomogeneity affect the formation of the condensate?



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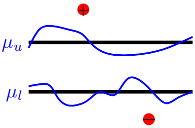
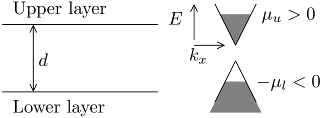
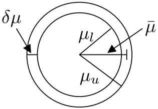




- This is similar to magnetic disorder in superconductivity.



$$\bar{\mu} = \frac{\mu_u + \mu_l}{2}$$

$$\delta\mu = \mu_u - \mu_l$$

Our calculation

There are three stages to the calculation:

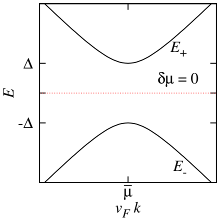
1. Theory for homogeneous unbalanced system.
   - Temporarily ignore inhomogeneity, calculate effect of imperfectly nested Fermi surfaces.
2. Analysis of realistic inhomogeneity.
   - Calculate statistics for $\delta\mu(\mathbf{r})$ in situations corresponding to contemporary experiments.
3. Combine these two results to assess impact of inhomogeneity on condensate formation.

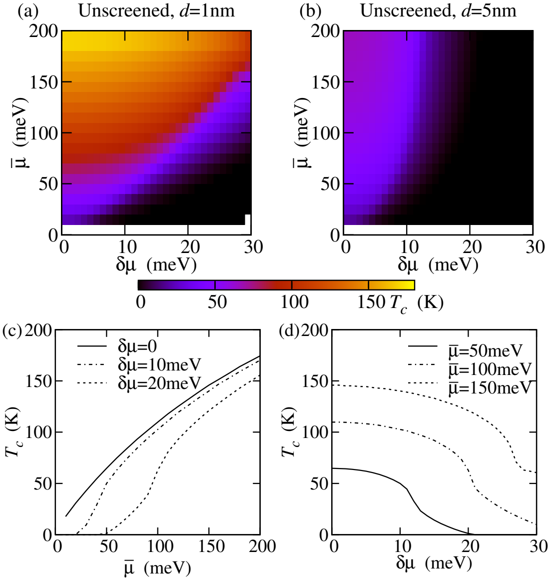
Step 1: T_c in clean system – unscreened interaction

Unscreened interaction:

$$V(q) = \frac{2\pi e^2}{\epsilon q}$$

- $\Delta(\delta\mu)$ unchanged for $\delta\mu < 2\Delta(0)$.
- Equivalent to Clogston–Chandrasekhar limit.
- No evidence of FFLO state.





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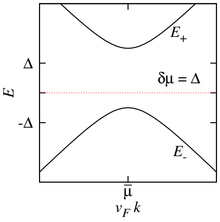

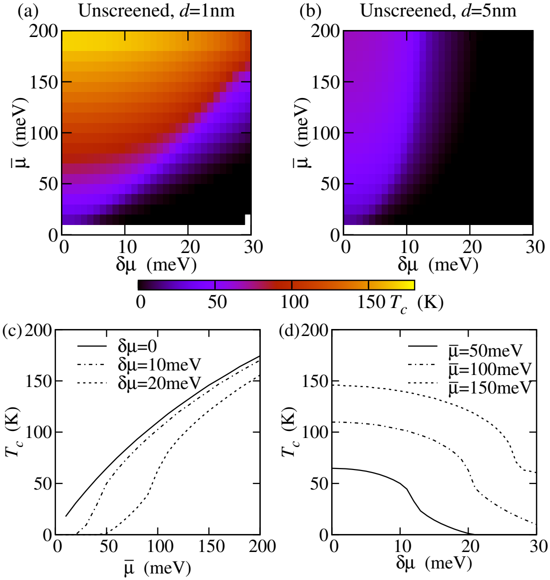

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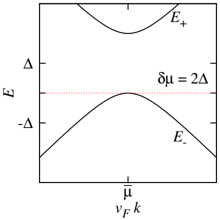

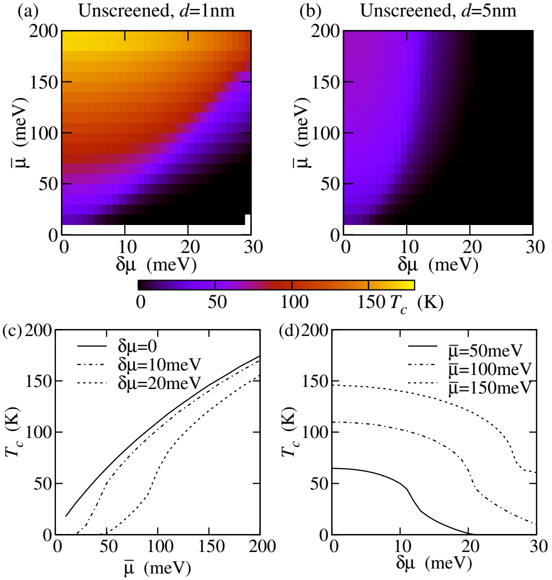

Step 2: Analysis of inhomogeneity

- Broken translational symmetry makes it impossible to analytically calculate exact density distribution for random disorder.
- We employ a numerical method: Thomas-Fermi theory.
- Functional method (à la DFT).
- The kinetic energy operator is also replaced by a functional of the density.
- This restricts the applicability to the regime where $|\nabla n/n| < k_F$, which is satisfied for double layer graphene.

Step 2: Analysis of inhomogeneity

- Energy functional is

$$E[n_u, n_l] = E_u[n_u(\mathbf{r})] + E_l[n_l(\mathbf{r})] + \frac{e^2}{2\kappa} \iint d^2\mathbf{r} d^2\mathbf{r}' \frac{n_u(\mathbf{r}) n_l(\mathbf{r}')}{\sqrt{|\mathbf{r}-\mathbf{r}'|^2 + d^2}}$$

- Layer energy functional includes contributions from disorder potential, and electron–electron interactions:

$$E[n] = E_K[n(\mathbf{r})] + \frac{e^2}{2\kappa} \int d\mathbf{r}' \int d\mathbf{r} \frac{n(\mathbf{r}) n(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} + \frac{e^2}{\kappa} \int d\mathbf{r} V_D(\mathbf{r}) n(\mathbf{r}) - \mu \int d\mathbf{r} n(\mathbf{r}).$$

- Ground state density landscape is found by numerically minimizing the energy functional with respect to the density distribution.
- Density distribution gives local chemical potential for each layer, and hence the local $\delta\mu$.

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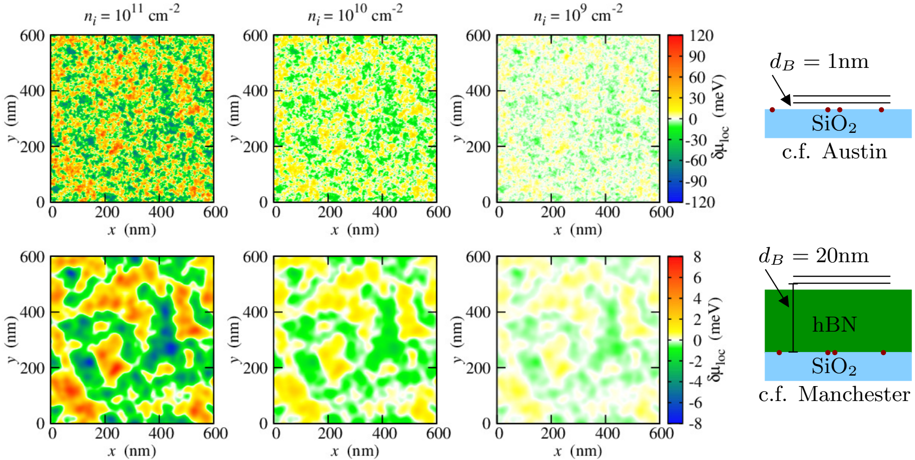
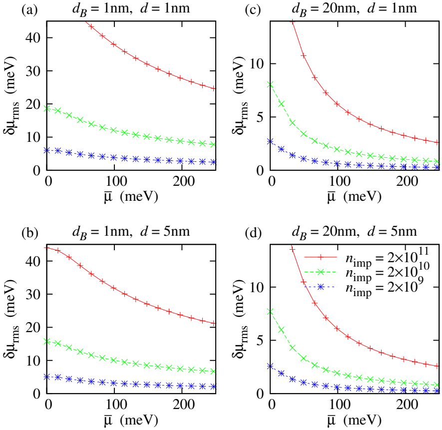
Step 2: Analysis of inhomogeneity

- Using TFT, we calculate the spatial profile of $\delta\mu$ for a given manifestation of charged impurity disorder:



Step 3: Links back to BCS theory

- We can perform this calculation for many (≈ 600) disorder realizations and collect statistics for the distribution of $\delta\mu$.
- This distribution characterized by it's root-mean-square (rms) value.



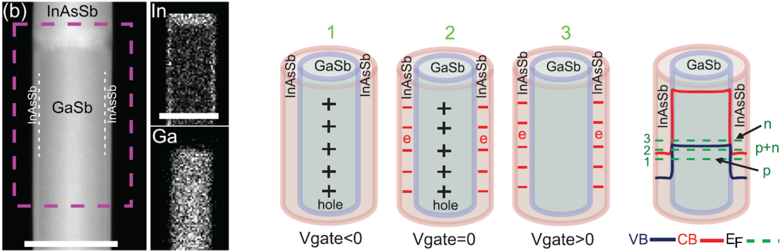
Predictions for Δ from BCS theory:

- Unscreened: $\Delta \sim 30$meV,
- Static screening: $\Delta \sim 0.01$meV,
- Dynamic screening: $\Delta \sim 1$meV.

Summary

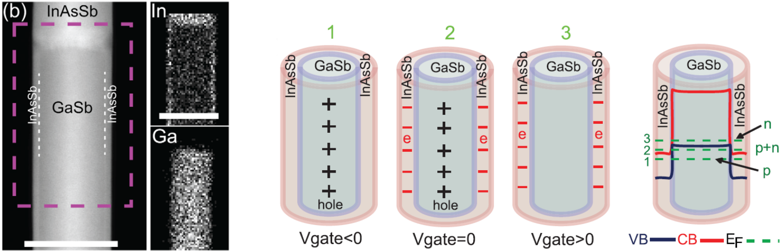
- Excitonic superfluidity is severely impacted by charge inhomogeneity in the two layers.
- The very cleanest contemporary samples may be on the cusp of allowing the condensate.
  - If estimates of the gap size using dynamical screening are to be believed.

Generalization to 1D



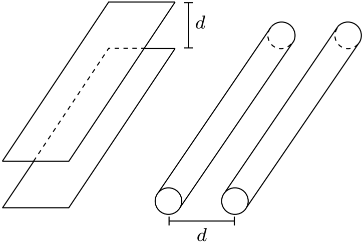
B. Ganjipour *et al.*, Appl. Phys. Lett. **101**, 103501 (2012).

Excitons in core-shell nanowires



B. Ganjipour *et al.*, Appl. Phys. Lett. **101**, 103501 (2012).

- Case 2 allows for pairing.
- Ground state populations.
- Alternate geometries also possible.



Assumptions and disclaimers

- No true long-range order in 1D.
- Particle correlations have power law decay $\Rightarrow$ quasi-order.

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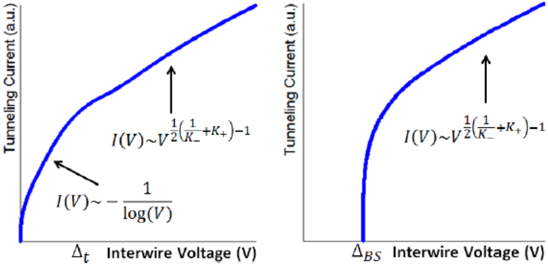
- No true long-range order in 1D.
- Particle correlations have power law decay $\Rightarrow$ quasi-order.
- In low density regime ($k_F d < 1$), system is effectively fermionic.
- Transport experiments on core-shell wires show no Luttinger liquid behavior.
  B. Ganjipour *et al.*, Appl. Phys. Lett. **101**, 103501 (2012).
- Bosonization treatment by Werman and Berg:



(a) Tunneling dominant regime (b) Backscattering dominant regime

Y. Werman and E. Berg, arXiv:1408.2718 (2014).

- Mean-field BCS theory in the particle-hole channel:

$$H = \sum_k \left[\xi_{1k} a_k^\dagger a_k + \xi_{2k} b_{-k} b_{-k}^\dagger + \Delta_k a_k^\dagger b_{-k}^\dagger + \text{h.c.} \right].$$

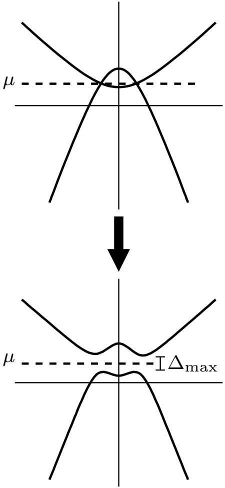
- The gap function is:

$$\Delta_k = \int dk' \, \frac{V_{\text{e-h}}(k'-k)}{4\pi} \, \frac{\Delta_{k'} \left[n_\alpha(k') + n_\beta(k') - 1 \right]}{\sqrt{(\xi_{1k} - \xi_{2k})^2 + 4\Delta_{k'}^2}}.$$

- Quasi-particle bands are:

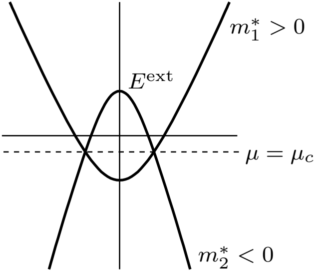
$$E_{\pm k} = \frac{\xi_{1k} + \xi_{2k}}{2} \pm \frac{1}{2} \sqrt{(\xi_{1k} - \xi_{2k})^2 + 4\Delta_k^2}.$$

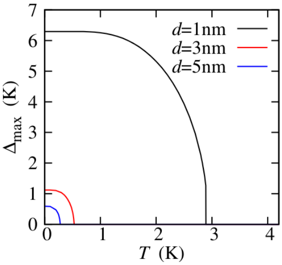
- Solve self-consistently for the gap function.
- Distance of closest approach of the two bands characterises 'condensate', label as Δ_{max}.



Excitons – results

- Case 2 allows for pairing.
- Optimal pairing when μ at band crossing (μ_c).





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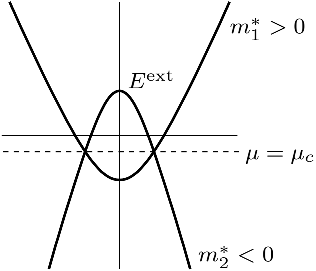

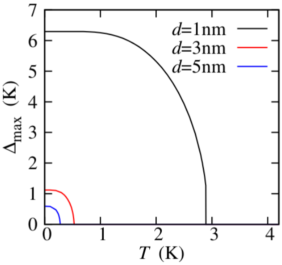

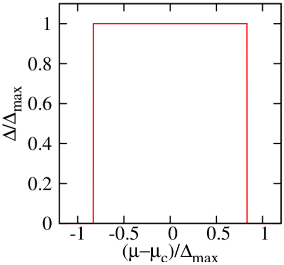

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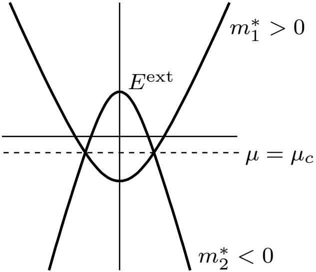

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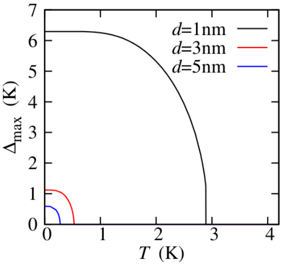

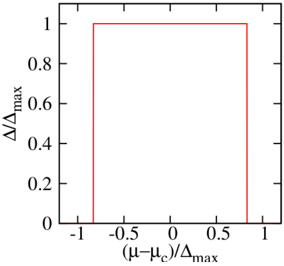

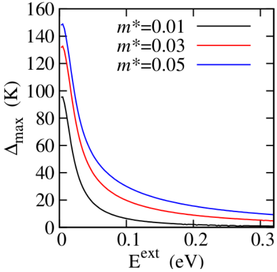

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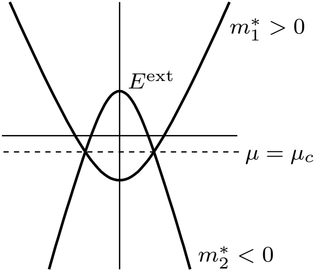

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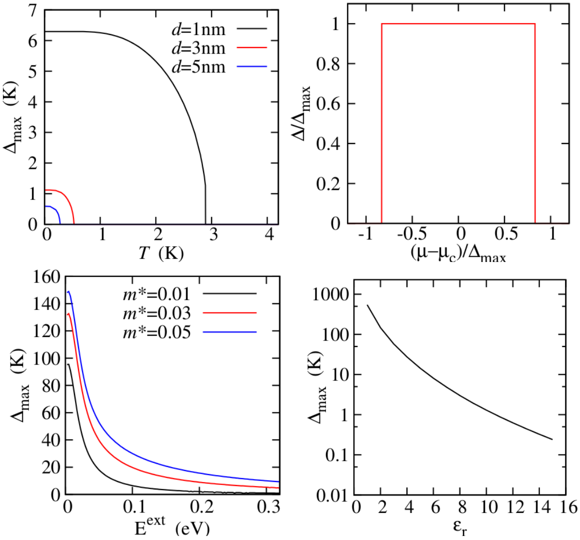

Summary

- Spatially separated excitonic systems are an exciting avenue for device design.
- Double layer graphene systems may be on the cusp of realizing the condensate.
  Phys. Rev. B **86**, 155447(R) (2012),
  Phys. Rev. B **88**, 235402 (2013).

  Collaboration with E. Rossi, S. Das Sarma, M. Rodriguez-Vega, and R. Sensarma.
- Parallel 1D systems may also be attractive hosts for exciton formation.
  arXiv:1408.7065.

Other interests

- 'Lateral heterostructures' of 2D materials.
- Optical properties of 2D materials.
- Tunneling conductance in strongly correlated systems.